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ANALYSIS OF COMMON CAUSE FAILURES COUPLING FACTORS AND MECHANISMS FROM AGEING POINT OF VIEW

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APSA Network Task 5
POS Task 4

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CONTENTS

Abbreviations 4
1. Introduction 5
   1.2 Overview of CCF analysis in current PSA studies 5
2. General remarks regarding links between CCF potential and ageing 8
   2.1 Initiating events analysis 8
   2.2 System modeling 9
   2.3 Data analysis 9
   2.4 Human reliability analysis 11
   2.5 PSA model quantification and interpretation of PSA results 12
3. Questionnaire proposed for the discussion about correlation between CCF coupling factors and ageing 13
   3.1 CCF coupling factors and preventive measures 13
   3.2 Developed questionnaire for discussion 18
4. Analysis of questionnaire answers 20
   4.1 Strength of connection of CCF coupling mechanisms with ageing 20
   4.2 Individual impact of CCF defense and prevention elements on strength of the links between coupling factors and ageing phenomenon 25
   4.3 Overall impact of CCF prevention elements on strength of the links between coupling factors and ageing phenomenon 35
5. Summary and conclusions 39
References 45

ABBREVIATIONS

CCF	**C**ommon **C**ause **F**ailure
CVNPP	**C**erna**v**oda **N**uclear **P**ower **P**lant
ENEA	National Agency for New Technologies, Energy and the Environment
I&C	**i**nformation **and c**ontrol
INR	**I**nstitute for **N**uclear **R**esearch Pitesti
JRC	**J**oint **R**esearch **C**enter
MGL	**m**ultiply **G**reek **l**etters (method)
NPP	**N**uclear **P**ower **P**lant
NRI	**N**uclear **R**esearch **I**nstitute Rez
PSA	**P**robabilistic **S**afety **A**ssessment
PRV	**p**ressurizer **r**elief **v**alve
SG	**s**team **g**enerator
WWER	**w**ater cooled **w**ater moderat**e**d **r**eactor

1. INTRODUCTION

Common cause failures analysis has been an integral part of PSA scope for nuclear power plants for several decades. Since plant systems are normally equipped with several mutually redundant trains, independent failures of components (failures located in just one train) are of pretty low importance (since probability of common occurrence of independent failures of several components located in different system branches equals to the product of low probabilities of individual failures). Thus, only multiple failures occurring at the same time (or after some small time shift) normally represent systems susceptibility to potential loss of function.
The investigation of ageing phenomenon impact on CCF potential was the main goal of Task 5 of the EC JRC Ageing PSA (APSA) Network. In the first phase of the project, some conclusions were formulated regarding the subject under investigation by NRI specialists on the base of expert evaluation of the links between CCF and ageing factors and specific data analysis of limited scope. To reduce the subjectivity of these conclusions, a questionnaire was developed, and sent to other project participants interested in the subject. Three project participants carried out detailed work, fulfilled the questionnaire and provided expert opinion regarding connection between common cause failure potential and ageing phenomenon. The inputs from the participants have been elaborated, evaluated and summarized in latter part of this report.

This report is devoted to searching for evidence regarding close links between CCF potential and ageing. On condition that the assumption about existence of such links with non-negligible impact on NPP operation risk is valid, it may be important to assess, what may be the strength of impact of such connection on the results of risk evaluation.

1.2 Overview of CCF analysis in current PSA studies

There are two types of elements of PSA model reflecting dependency - dependent failures described in an explicit manner in fault tree logic and implicitly present "residual" dependencies represented by "CCF basic events". The explicitly modeled functional dependencies have always formed an integral part of nuclear power plants PSA models. However, they have not required any special treatment regarding modeling, quantification and data acquisition beyond the common requirements to system analysis and well done modeling of dependent links in system functionality. Thus, the following overview will be related (in accordance with the goal of analysis in this project) to residual CCF.

Two basic problem areas have to be solved in residual CCF analysis in the phase of PSA model development:

- which points in the system model logic are the right ones to be covered by primary events related to residual common cause failures (**CCF modeling**)
- what quantitative values of CCF potential parameters (CCF probabilities) are the most appropriate in the individual cases (**CCF quantification**).

The analysis of plant specific experience is very important part of the process of creation of CCF groups. In case that CCF potential is indicated in plant specific experience, CCF group and primary event is developed for the mutually redundant components under concern, provided that it can not be proven that an absence of such basic event does not have any impact on global PSA results. The indication of CCF potential does not mean necessarily occurrence of some event with complete loss of all components in CCF groups in operational history, rather it may include also any event with complete loss of some subgroup of components or even an event with evidence of synchronous incipient failures or degraded status of more than one component from CCF group.

The worldwide experience is that CCF events belong to rare events, which are very important from point of view of safety and risk of plant operation (as it can be proven with analysis of typical list of minimum cut set after PSA model quantification). For that reason, CCF primary events are included into PSA model by default, even without any support of plant specific operational experience. This is typically done for selected types of components, which have been generally found as susceptible to CCF potential. The most frequently used candidates are:

- motor operated valves
- pumps
- safety relief valves
- air operated valves
- solenoid operated valves
- check valves
- diesel generators
- batteries
- inverters and battery chargers
- circuit breakers (if modeled as separate component in PSA study).

As it can be seen, active components can be found in the list of CCF vulnerable component types mostly, which are normally modeled in PSA studies (from point of view of *independent* failures), whereas failures of so called passive components are expected as having negligible impact on plant operation risk (at least as a part of plant response to initiating event occurrence). Still, this may not be true from point of view of common cause failures, where, for example, debris blockage of redundant or even diverse pump strainers is significant multiple failure phenomenon typically modeled in PSA studies (in case of WWER reactors, this example is fully supported with operational experience in case of emergency core cooling systems or circulating water systems, for example).

In addition, common cause failure groups can be established by using logical, systematic process of searching for similarities in design and operation, particularly devoted to:

- service conditions
- environmental impacts
- design or manufacturer
- maintenance.

These (or more detailed) aspects of possible CCF potential, so called **coupling factors**, do represent, if present, basic elements of difference between common cause failures and a coincidence among several independent failures. The search for coupling factors is usually done systematically, in sufficient level of detail, by means of repeatedly used checklist. The following list of checklist items used in searching for CCF vulnerability, presented in [1], can be used as an example:

- **component type** (e.g. motor operated valve, pump, circuit breaker), including any special design or construction characteristics
- **component use**, for example system isolation, flow direction, physical variable measurement, electric power supply
- **component manufacturer**

- **component internal conditions**, typically related to absolute values, trends or dynamicity of changes of basic physical variables (pressure, temperature, flow, chemistry and radioactivity characteristics, power, voltage, neutron flux etc.)
- **component boundaries and system interfaces**, as common suction/discharge header (but not including common support systems, where the dependent failure effect is usually modeled explicitly in PSA, not by means of residual CCFs)
- **component visual similarity** and corresponding supporting factors, as location in the same room/building, similar parts, control panels which look identical, similar tables with component identification data
- **component external environmental conditions** represented by temperature, humidity, barometric pressure range, atmospheric particulate content and concentration etc.
- **component common status conditions** and operating characteristics as normally closed/open, (dis)energized, running, stand-by
- **component testing and maintenance procedures** and characteristics - test interval, test configuration or lineup, planned or preventive versus corrective maintenance strategy, maintenance configuration and effect on system operation.

Using of the checklist for CCF identification is typically supplemented by plant walk-down. Any group of components which share similarities in one or more characteristics above represents potential point of CCF vulnerability. However, as soon as automatic using of the list would lead to pretty extensive list of CCF groups, a combination of several commonalities may be required in order to create manageable list.

In the list of rules above, identical, functionally non-diverse, active components are subjects of analysis. As soon as the principle of diversification has been applied in plant design as preventive measure against CCF events occurrence, the assumption of independence is a good one and is usually supported by operating experience data. However, when diverse mutually redundant components have piece parts that are identical, the components should not be assumed fully independent. In such case, it is possible to break down component boundaries, to represent common piece parts with specific PSA model primary events and to create CCF group from non-diversified inner components.

2. GENERAL REMARKS REGARDING LINKS BETWEEN CCF POTENTIAL AND AGEING

The main goal of the analysis performed in the first phase of the project [5] was to formulate some general conclusions regarding links between CCF potential and ageing, which could be further elaborated, extended and concretized in international discussion. Those conclusions were briefly summarized and were used as inputs for the developed questionnaire.

The basic conclusion and statement that can be made on the base of detailed analysis of operational experience and matching it with theoretical assumptions is that there is some evidence about correlation between ageing and factors influencing strength of common cause failure potential, so that common cause failures may be treated also as one specific item of methodologies of covering ageing phenomenon in the studies of probabilistic safety assessment, developed in future. This basic conclusion may be further elaborated into useful details that address issues of various kind, which are important for probabilistic modeling and which interfere with various regions of probabilistic safety assessment scope. In the following paragraphs, these preliminary conclusions are discussed in connection to specific probabilistic safety assessment aspects.

2.1 Initiating events analysis

Basically, all initiating events can be divided into several categories with different susceptibility regarding common cause failure potential and ageing:

- loss of piping integrity (LOCA, secondary circuit piping breaks, PRI-SE loss of integrity)
- loss of safety important systems, loss of support systems
- human related events.

Typically, CCF potential is modeled only for active systems in current PSA and, for these systems, the CCF-ageing link may be an important subject of analysis with significant impact on "loss of safety important systems" part of initiating event spectrum. However, as it can be seen from operational history and test and maintenance records, there is definitely strong ageing potential present in many piping sections (particularly those, where common preventive measures fail due to some objective or subjective reasons - they may be difficult to be reached during tests, for example) with evident links to some common cause failure coupling factors. As a consequence, connection of CCF potential and ageing may have non-negligible influence over the complete spectrum of initiating events defined in PSA model, perhaps with some limitations regarding events caused directly by human, where the connection with ageing is usually evaluated as weak.

It should be pointed out that possible impact of ageing may influence the approach to screening, as well. Each of initiating events, which was screened in some phase of development of PSA model due to very low frequency, should be reassessed (at least qualitatively) after some time period and the assumption about low frequency value should be verified, because the value could increase due to ageing-CCF effect. In addition, assumptions made regarding plant response to initiating event before screening that initiating event out of the model should be checked, as well, because the validity of them could be also affected with increased CCF-ageing link.

2.2 System modeling

Frequently, the strength of CCF ageing interaction may be also a consequence of the style adopted in the given PSA project regarding system modeling. If the common cause failure modeled by some fault tree basic event represents, in fact, failure of common, separable component that was, for some reason, included into the component boundaries of all (macro)components in the CCF group under concern and therefore not modeled explicitly in PSA, the best solution of possible addressing of ageing effects in the system model may be separation of this component into a newly defined basic event, which can be studied in simpler way regarding non-constant failure potential due to ageing than in case, it is part of more complex structure of common cause failure basic event, A typical example supported by operational history evidence is failure of some relay, not modeled in PSA explicitly, that leads to failure of several valves in mutually redundant trains of the same system.

An opposite case to that mentioned in previous paragraph may also appear in PSA model. Some cases of common cause failures taken from plant operational history can be found as fairly hidden in the structure of PSA model, because the corresponding failure mechanisms are modeled within the bounds of mutually redundant segments inside the component boundaries. These cases of CCF events are lost for the given pre-defined level of PSA model detail (not able to cover too tiny CCF effects), as a consequence, some useful inputs into the solution of CCF versus ageing topic may be lost, as well. This loss may be prevented with increasing of level of detail of analysis of the individual components in PSA model by splitting selected components (basic events) into several smaller ones and redefinition of component boundaries.

It seems that „big“ components show up more intensive connection with ageing in CCF symptoms than “small” components, because common cause failures of “small” components are more frequently consequences of some sudden shock without any latent origin. In addition, the “big” components' failure events (including CCF) are not typically solved with component replacement in plant operation and maintenance practice, what is often seen as optimum strategy for smaller (and not that expensive) pieces of equipment, keeping the "small" components of the system not that old as the "big" ones and thus less susceptible to the effect of CCF-ageing link (in case of CCF failure of several "small" components, the probability of replacing them is even higher than in case of one component independent failure). As a consequence, division of components under concern into the categories of “big components” and “small components” may be, from point of view of CCF-ageing analysis, viable alternative to more frequently used division into the categories of “passive” and “active” components

2.3 Data analysis

Component data analysis background is commonly structured according two key attributes - **component types** and **failure modes**. For the individual component types and failure modes - independent failure potential has been proven as highly unbalanced in data analysis - both in general, and for concrete plant specific conditions of nuclear technology operation. In case of CCFs, the individual independent failure potential is further combined with different strength of coupling factors effects, making the spectrum of failure potential distributed in different, but also unbalanced way. The same conclusion can be made for ageing phenomenon - some components age much faster than the others and failure potential spectrum is changed once more over components types, as soon as combined effect of independent failure causes, CCF coupling factors and ageing is taken into consideration.

Some subjective assumptions can be made about the strength of CCF-ageing link (as a part of total failure potential) for the individual types of components and selected failure modes on the base of limited operational experience and expert judgment. Due to high level of subjectivity, it is desirable to up-date and refine these evaluations by adding much broader scope of experience from nuclear power plants worldwide. The basic scheme for initiation of discussion about strength of links between CCF potential and ageing may look like in the following table. The same colour coding as that used and explained in Table 6 in Section 3.3 is used. Similar, even more detailed table can be developed, where component types and failure modes are directly combined for the purpose of evaluation of strength of CCF and ageing link (the assumption is made directly for pump failure to start, for example).

Table 1: Possible scheme for evaluation of CCF-ageing link for the individual component types and failure modes

Component types/failure modes	CCF-ageing link	Comments
Component types		
pump standby	**medium-strong**	
pump operated	**medium**	
motor operated valve	**medium-weak**	
control valve	**medium**	
circuit breaker	**medium-weak**	
dieselgenerator	**medium**	
....	...	
Failure modes		
failure to start	**medium**	
failure to run	**medium**	
loss of integrity	**medium-strong**	
plug	**medium-strong**	
failure to open	**medium**	
failure to close	**medium-weak**	
failure to reclose after opening	**medium-weak**	
...	...	

Some selected component failure modes, which are sensitive to CCF potential, can be seen **a priori** as candidates for ageing related analysis, for example

- **plugging of** (narrow) piping path
- **loss or exposure of piping system integrity** - both **external**, with coolant loss out of the boundaries of piping system (not only loss of integrity of piping walls, but also leaks from pressurized system through "active" component boundaries - safety valve, for example), and **internal** - leaks through component boundaries inside the piping system - check valves, typically, but also other valve types, potentially
- **erosion of cables insulation,** potentially causing both electric power supply and I&C components common cause failures

- common cause failures of **terminal switches**, loss of some other electric power supply components types (**buses**)
- failure modes of **difficult-to-be-reached components** (valves located on draining piping lines).

It should be pointed out that favorable failure statistics (low number or no failures) derived on the base of component availability tests (covering either component reliability in general or common cause failure potential specifically) **may not represent necessarily an impulse for screening out the given set of components from further ageing related analysis**, because the availability tests may be frequently oriented rather to external availability confirmation symptoms than to real status of the component, which may degrade during component life, as being subject of failure modes with hidden latent effects.

If there is **one given CCF event** taken from operational history of components belonging to **sufficiently broad population** and there is suspicion about some link of CCF mechanisms to ageing phenomena, **the hypothesis about CCF-ageing relevance should be supported with other pieces of evidence** (additional events related to the population as a whole) during some selected sufficiently long time window, in case that such additional evidence is missing, the relation of the given CCF event to ageing can be evaluated as illusory (on high level of statistical confidence)

Three classes of events can be defined in future analyses of CCF-ageing link, which may reflect level of randomness of event occurrence on time line:

- **time unconditional**
- **time potentially conditional** (events, where time conditionality can not be fully negated on the base of surveyed facts)
- **highly probably time conditional** (on the base of available information about longer component operation time period, due to relation to failure mode a priori evaluated as ageing related, due to identification of coupling factor sensible regarding ageing, or due to combination of presented reasons).

The first category may be screened out from the analysis to save the resources; the remaining two categories should be analyzed more in detail

There is one more specific aspect of CCF-ageing links related analysis that is usually not addressed directly data analysis scope as a part of PSA project - **impact of maintenance strategy**. If maintenance rules lead to **replacement** of damaged components with new ones, the process of ageing may be significantly suppressed, because new components gradually appear in operated technology on the places of original equipment. It is clear that replacement as maintenance strategy can never suppress ageing completely, because significant part of technology elements will never be removed and replaced and there will be always strong links between "new" (replaced) pieces of equipment and old segments of it, which may cause failure ot new elements, as well. Still, the overall impact of replacement should be analyzed, for example in relation to component types and failure modes.

2.4 Human reliability analysis

One of the conclusions that can be made, even on the base of limited operational experience, is that common cause failures with significant effect of human factor can be frequently screened out at the beginning of ageing related analysis, because human factor part, as an element of the spectrum of causes and symptoms of common cause failures, is almost always connected with instantaneous or short-term effects. Even in case of some long term persisting negative human factor characteristics, some kind of ageing related stable trend of reliability decreasing can not be normally expected. The only exception are some hardly identifiable psychological factors (burning out syndromes, loss of perspective and motivation, influence of human individual ageing) that may be still better treated with special methodologies devoted to human and organizational factors problems than with ageing (or CCF) models.

2.5 PSA model quantification and interpretation of PSA results

Safety importance of CCF-ageing connection is given, first of all, with the common cause failure characteristics of the events (location of corresponding PSA CCF basic event in the logical structure of PSA model), the ageing related characteristics are of somewhat lower importance nowadays, but the contribution of ageing to the total level of risk may increase up to the level postulated with component RAW (*risk increase factor*) value (but not higher) provided that no effective measures are adopted to prevent recurrence of ageing caused CCF events. As a consequence, **RAW value of the given basic event can be used for conservative formal description of possible maximum influence of the CCF group, as soon as CCF failure probability is getting higher due to ageing.** Such application of RAW is simple and straightforward in case that all dominant risk spectrum contributors (minimum cut sets) contain just one basic event connected with interaction between common cause failure potential and ageing. Possible existence of minimum cut sets with more than one of such primary events would need specific treatment.

In the context of processes passing during nuclear power plants operation, both the characteristics of common cause failures and the ageing phenomena attributes show a number of common general features, valid for major part of worldwide operated nuclear reactors. Thus, it is possible, as further step in analysis in future, to suggest additional verification of the conclusions made in this work. Current generic data sets, which are at disposal, for example, in [8], [9], [10], [11], cover, although by lower level of detail than the sample of specific information used in this project, much bigger volume of events so that they may provide a relatively broad statistics.

Connection of components ageing with common cause failures should be seen as just one specific (still, potentially important from point of view of overall PSA results) topic of treatment of ageing as a whole in the PSA study. This broad topic can be found in early phase of methodological development nowadays. The newly proposed methodologies should be able to be extended in straightforward manner, but lack of both generic and specific suitable data (even more critical than in case of basic ageing models connected with individual component failure potential) will have to be solved in some manner.

3. QUESTIONNAIRE PROPOSED FOR THE DISCUSSION ABOUT CORRELATION BETWEEN CCF COUPLING FACTORS AND AGEING

The potential relation between common cause failures and ageing phenomenon was studied in [5], and this relation can be seen as a quite new subject of analysis - although CCF had been an integral element of NPP probabilistic safety models for decades, ageing has been analyzed very rare in recent practice of PSA models that is typically based on an assumption of constant component failure rate.

One of the main goals of the analysis was to study the most important common cause failures initiating factors (so called *CCF coupling factors* in [2]) from point of view of relation to ageing phenomena. The structure of factors analyzed has corresponded to the typical schemes of CCF potential contributors, as identified, specified, analyzed in detail, and classified in systematic manner in the methodologies forming the base of qualitative as well as quantitative CCF analyses in worldwide developed nuclear power plant risk models, particularly in [2], and also in [3], [1], [6], adopted for specific conditions of Czech NPP operation in [7], [8], [9]. The analysis has not been limited to complete list of "negative" factors increasing CCF potential only, but it has included also "positive" factors representing a kind of prevention and correction measures applied with the aim to avoid occurrence and recurrence of CCF events, whether related to ageing or not.

In [5], the evaluation of both CCF coupling factors and CCF prevention measures from point of view of relation to ageing had to be based on a big deal of subjectivity. Although a limited sample of plant specific operational experience from Czech NPP was available, further supported with plenty of generic information taken from [10], [11], [12], [13], for example, one of the final conclusions made was that it would be useful to repeat such kind of analysis in a broader forum. This conclusion was further supported during some internal discussions with other JRC Ageing PSA Network members. The main output from these discussions was the idea to develop a kind of questionnaire supporting such discussion.

In the questionnaire, two main topics were proposed for the discussion:

> *What is the strength of relation between the individual CCF coupling factors (contributing to total CCF potential) and ageing phenomenon?*
>
> *For those CCF coupling factors, which have been evaluated as coincident with ageing phenomenon (at least medium level of coincidence) - what is the effect of CCF prevention measures on the coupling factor versus ageing relation?*

The basic information about CCF coupling factors and CCF preventive measures, as defined in the fundamental material [2], is summarized in Section 3.1 of this document.

3.1 CCF coupling factors and preventive measures

In the up-to-date risk models of operation of complex technologies, common cause failures (if analyzed) are understood as a result of combination of two phenomena:

- **<u>triggering</u>** (independent) **<u>event</u>** leading to unavailability of the (first!) component that, in most cases, does not further develop
- occurrence of conditions for **<u>failure coupling</u>** and loss of more mutually redundant components of the same type and function, finally challenging availability of the system as a whole, i.e. demonstration of presence of common cause **coupling factors**.

<u>Both</u> these **<u>phenomena</u>**, which form common cause failure together, may be **<u>related to ageing</u>**. These relations to ageing may be in coincidence or independent. The triggering event relation to ageing may be solved in detailed analyses of data records representing **<u>independent</u>** failures and addressing them in the basic component ageing models. Still, the real CCF occurrence potential is put into effect at the time point, component failure **starts expanding** to further components.

The total level of CCF potential, particularly of the “expanding part”, is not limited to the real presence of common cause coupling factors only. The other side of the story is **quality and strength of adopted strategy of CCF prevention**. For most of the factors initiating and strengthening CCF event, elements of prevention and defense (common cause anti-factors, in fact) can be identified during analysis of plant operation practice, which may become part of CCF analysis, as well. In addition, similarly to the coupling factors, these anti-factors can be investigated from point of view of connection with ageing. As a consequence, analysis of CCF-ageing link may consist of two parts - analysis of development of **CCF causing coupling factors over time** and parallel analysis of **prevention and defense factors limiting the CCF potential**.

CCF coupling factors are divided into three basic categories: [2]

- design, hardware based coupling factors
- operation based coupling factors
- (external) environment based coupling factors.

The hardware based coupling factors propagate failure mechanisms among several components due to identical design and physical characteristics of the components. There are two subcategories of hardware based coupling factors:

- hardware design
- hardware manufacturing and installation quality.

There are two groups of design-related hardware couplings: system level and component level. System level coupling factors include features of the system of groups of components **external** to the components that cause propagation of failures to more than one component. Component level coupling factors are caused by features within the boundary of each component.

The following coupling factors belong to the **<u>hardware design</u>** category:

- **same physical appearance**: The cases where several components have the same formal or informal identifiers (color, letter coding, number, and size/shape, as well). This can lead to components misidentification by the operating or maintenance staff. ***Example****: Removing insufficiently identifiable pumps from operation to maintenance.*
- **system layout/configuration:** The system layout and configuration coupling factors refer to the arrangement of components to form a system. ***Example:*** *Containment spray pumps failed to meet differential pressure requirements due to air binding at the pump suction, resulting from a system piping design error.*
- **same component internal parts**: The same component internal parts coupling factor refers to characteristics that could lead to several components failing because of the failure of similar internal parts or subcomponents. This coupling factor is used when failure investigation is limited to identifying the subcomponents or piece-part at fault, rather than the root cause of failure of the piece-part. ***Example:*** *High pressure coolant injection pumps tripped during tests. The cause was failed Teflon rupture discs, which were inadequate for their intended purpose.*

- **same maintenance/ test/ calibration characteristics:** The same maintenance/ test/ calibration characteristics refer to the similarity in maintenance/ test/ calibration requirements, including frequency, type, tools, techniques, and personnel-required level of expertise. ***Example:*** *Two diesel generators failed to load due to shutdown sequencer problems. During one diesel generator failure, the diesel could not be loaded manually or automatically due to dirty contacts on the sequencer. In the second diesel failure, the sequencer clutch stuck due to being dirty and needing lubrication. The cause was determined to be the lack of quality of preventive maintenance.*

Hardware quality coupling factors refer to characteristics introduced as common elements for the quality of hardware. These include:

- **manufacturing attributes:** The manufacturing attributes coupling factor refers to the same manufacturing staff, quality control procedure, manufacturing method, and material.
- **construction/ installation attributes (both initial and later modifications).** This factor refers to the same construction/ installation staff, construction/ installation procedure, construction/ installation testing/verification procedure, and construction/ installation schedule.

The **operational based** coupling factors are those coupling factors that propagate failure mechanisms on account of identical operational characteristics among several components. The categories of operation based coupling factors are:

- **same operating staff** - this coupling factor refers to the events that may happen, if the same operator (team of operators) is assigned to operate all trains of a system, increasing the probability that operator errors will affect multiple components simultaneously. (***Example:*** *All emergency service water pumps were found in tripped status. The trips were the result of an emergency engine shutdown device being tripped. The operations personnel did not recognize that the trip devices has to be reset following testing.*)
- **same operating procedure** - The same operating procedure coupling factor refers to the cases when operation of all (functionally or physically) identical components is governed by the same operating rules. Consequently, any deficiency in the procedures could affect all these components. (***Example****: Two auxiliary feed water pumps failed to develop the proper flow output. It was determined that the manual governor speed control knobs had been placed in the wrong position due to an error in the procedure.)*
- **same maintenance/ test/ calibration schedule** - This coupling factor refers to the maintenance/ test/ calibration activities on multiple components being performed simultaneously or sequentially during the same maintenance/ test/ calibration event. (***Example:*** *A number of breakers in electric power supply system failed to close due to dirt and foreign material accumulation in breaker relays. Existing maintenance and testing requirements allowed the relays to be inoperable and not detected as inoperable until the time that the breakers were called on to operate*).
- **Same maintenance/ test/ calibration staff:** This coupling factor refers to the same maintenance/ test/ calibration team being in charge of maintaining multiple systems/ components. (***Example:*** *The component cooling water pump high bearing temperature alarm sounded. The pump bearing had rotated, blocking oil flow to the bearing. The apparent cause was pump/ motor misalignment. Eleven days later, the same symptoms appeared in operation of the other component cooling water pump.*)
- **same maintenance/ test/ calibration procedures:** Common procedures could also be responsible for propagation of errors due to procedural errors and operator's wrong interpretation of procedural steps. This is a consequence of (appropriate, from many points of view) approach to procedures development strategy, where it has been recognized that for non-diverse equipment, it is impractical to develop and implement diverse procedures.

The **<u>environment based</u>** coupling factors are those coupling factors that propagate failure mechanisms via identical external or internal environmental characteristics. The following factors belong to this category:

- **same plant location**: The same plant location coupling factor refers to all redundant systems/ components being exposed to the same environmental stresses because of the same plant location (e.g. flood, fire, high humidity, and earthquake). The impact of many these environmental stresses is normally modeled explicitly (by analyzing the phenomena involved and incorporating their impact into the plant/system models) in current PSAs. Other environmental factors such as high humidity and temperature fluctuations are typically considered in CCF analysis and treated parametrically. (***Example:*** *Common trip of components due to weather effects - freezing up in winter or overheating in summer.)*
- **same component location:** The same component location coupling mechanism refers to multiple systems exposed to similar environmental stresses because of concrete location of systems/ components (for example vibration, failure of ventilation systems, heat generated by other components, accidental human actions etc.). ***Example:*** *1) Both auxiliary feed water pumps were sprayed by stream of water from broken piping of service water system. Auxiliary feed water system was lost completely.*
- **internal environment/ working medium:** The internal environment/ working medium factor refers to commonality of multiple components in terms of the medium of their operation such as internal fluids (water, lube oil, gas, etc.). Operating with the same dirty water, for example, could cause multiple failures due to corrosion (just straightway, this factor can be seen as implicitly very important from point of view of CCF-ageing connection). ***Example:*** *Four of six service water pumps failed due to wear causing a high pump vibration. The pumps take a suction on ocean, and the failures were caused by excessive quantities of abrasive particles in the ocean water*

Similarly to the factors increasing CCF potential, the spectrum of preventive factors is fairly broad. It can be divided into several basic categories:

- applications of diversity principles
- creation of functional of physical barriers
- adjustment of testing and maintenance policy
- extra redundancy.

The **<u>diversity principles</u>** (**D**) can be oriented to diversity of function (**functional diversity**) (**D_1**), diversity of design of the component (**equipment diversity**) (**D_2**) or to plant staff maintaining and operating the components and systems (**staff diversity**) (**D_3**). The main idea of diversity application is (to a big difference from application of principles of „common“ redundancy, where an emphasis is put upon *identity* of mutually redundant components) using *as far as possible different* concepts for ensuring availability of some very similar or identical functions (functional diversity) or, at least, using of different equipment type for achieving of the same goal (diversity in component design). Diversity in design can be supported with using of different construction elements, physical characteristics, manufacturing or operation principle. Another important variant of diversity is diversity in staff, i.e. using different teams and individuals to install, maintain and/or test, and operate redundant trains.

From theoretical point of view, **<u>diversity should be seen as the basic strong mechanism of defense against CCF</u>**, leaning on an assumption that the components of different design, operated in different ways, will be subject of different failure mechanisms with very low probability of common failure at the same time point, with the exception of major external environmental factors such as seismic events. Still, diversity has only been used to a limited extent in nuclear power plants design and operation. Even in cases where the concept has been used, there are often sources of dependence that may make the components susceptible to coupling mechanisms, often in the form of similar piece-parts and common location.

Physical or functional barriers (**B**) as a CCF defense principle are usually oriented to the following classes of measurements:

- **spatial separation** of components (different location, relocation without further changes I design or operation) (**B_1**)
- creation of special **physical barriers** (**B_2**)
- construction of **interlocks** in the systems of equipment control (**B_3**)
- **removing of cross-ties** between redundant trains (**B_4**).

The most complete implementation of spatial separation strategy is putting redundant equipment in **separate locations** that are not connected "any way" (including using different heating and ventilation systems for the individual trains). This way of protection (**B_1**) may even enhance defenses against CCF related human errors in realignment of redundant trains of equipment because the operator could not rely anymore on the lineup of one train, which could be incorrect, to line up the other train.

A simpler variant of defense is to provide **physical barriers** (**B_2**) that protect against harsh environments (missiles, coolant stream). However, there are environmental impacts; physical barriers do not provide protection against, as high temperature in the common location of the pumps or other sensible components.

Special **interlocks** are often used as defenses in instrumentation and actuation logic of safety related systems so that only one component at a time can be taken out of service for testing or maintenance, preventing CCF related human and organizational error (**B_3**).

The problem of **removal of cross-ties** (**B_4**) is that, although positively reducing some postulated CCF impact, it could have a detrimental impact regarding other causes of failure by decreasing the level of equipment redundancy in some way (air support system of pneumatic components may be lost, due to existing cross-ties, even after loss of integrity of just one train, but provided that the cross-tie is removed completely, available train of the system can not be used instead of other train that was put into maintenance for some reason).

The **changes in maintenance policy** (**U**) can be seen as relatively strong means of current **total** CCF potential limitation, but the influence on CCF related ageing phenomena is more or less indirect. **Staggering** test and maintenance activities offer some advantages over performing these activities simultaneously or sequentially. First, it reduces the coupling associated with human-related failures that are introduced during test and maintenance activities. The probability that an operator or technician repeats an incorrect action is lower when test or maintenance activities are performed months, weeks, or even days apart, than when they are performed a few minutes or a few hours apart. A second potential advantage of staggering test and maintenance strategy relates to the exposure time of CCF event. If multiple components are indeed failed because of a CCF event and if this type of failure is detectable by testing and inspecting, then evenly staggering these activities minimizes the time that multiple components would be failed because of CCF, by reducing the exposure time. Still, it should be taken into consideration that these positive CCF prevention factors are not directly connected with ageing attributes.

In general, **additional level of redundancy** can not be regarded as a defense against CCF in the same way as other defenses, since the definition of CCF is that they *override redundancy*. Still, increasing of redundancy level may have beneficial effects and, in fact, may create new level of operational diversity. The additional level of redundancy may be created in classic way (by extending number of system trains by one more of the same design and operation rules), or, more progressively, with full application of diversity principles. There is a broad spectrum of possibilities regarding diversity level between two boundary cases, with some above mentioned CCF potential prevention principles taking place to some extent. For example - the system of three identical pumps with symmetric design with partial CCF defense by physical isolation of the pumps in partially separate cells may be supplemented by fourth pump produced with the same manufacturer, working the same way as the original pumps, operated with the same staff, but located in completely different cell far away from the rest of the system.

3.2 Developed questionnaire for discussion

All CCF coupling factors presented in Section 3.1 can be studied from point of view of connection with ageing mechanisms. In the following table, a kind of summary on CCF coupling factors versus ageing attributes is proposed. The table consists of three columns. In the first column, CCF coupling factor is defined. The strength of the given factor relationship with ageing may be approximately qualitatively measured in the second column, as it has been found indicated both in operational experience and in theoretical studies, the evaluating subject/ specialist is familiar with. The strength value assigned in the second column of the able may be commented in the last column (reflection in operational experience, assumptions etc.). The following scale is proposed for specification of strength value of CCF coupling factor and ageing phenomenon relation:

- insignificant
- medium- weak
- medium
- relatively strong
- strong.

All presented elements of defense strategies against CCF belong to important prevention means against CCF events occurrence. However, the effects of application of these prevention measures from point of view of CCF connection with ageing phenomena may differ significantly, from really important to as low as insignificant.

The influence of the individual prevention factors was proposed to be evaluated on the base of available operational experience and expert judgment. The CCF factors (regarding links with ageing) were listed, and every column of the table represents some strategy of prevention of CCF occurrence. The color codes define the strength of potential influence of prevention factor on the strength of link between CCF potential and ageing phenomena. A number identifier of comment/ note may be put in the individual fields of the table referring to comment/ note below the table

However, is does not make sense to analyze the relation of preventive measure to ageing as soon as the coupling factor prevented has no significant relation to ageing phenomenon. **Thus, only those coupling factors evaluated as having at least medium relevance to ageing should be taken into consideration, for further analysis.**

It should be emphasized that **the relative effect of the given prevention measure strategy on the link between CCF coupling factors and ageing is evaluated**, **<u>not the overall preventive effect on the coupling factors</u>**. In other words, if the strength of relation of the given CCF coupling factor and ageing is *medium* only, but the preventive measure under consideration erases the relation completely, the total effect of preventive factor should be evaluated as *high*.

The summary effect of the individual prevention strategies (across all relevant coupling factors) may be evaluated intuitively by means of the same scale as in previous cases.

4. ANALYSIS OF QUESTIONNAIRE ANSWERS

Three participants in the project sent fulfilled questionnaire forms back making possible very interesting comparison and further discussion about the subject of investigation. Two participants are from Romania, one from Italy, what makes altogether (with NRI as discussion initiator) a sample of four contributors:

- Institute for Nuclear Research Pitesti (INR)
- Cernavoda Nuclear Power Plant (CVNPP)
- National Agency for New Technologies, Energy and the Environment (ENEA)
- Nuclear Research Institute Rez (NRI).

All participants fulfilled and provided answers to all questionnaire tables. All these inputs are summarized, compared and commented in this chapter. It should be emphasized that all the inputs were developed in completely independent way so that they really represent four **independent** opinions of specialists in the field.

4.1 Strength of connection of CCF coupling mechanisms with ageing

This section is devoted to basic common cause failure coupling mechanisms. In Table 2, evaluations of strength of link between the individual most important coupling mechanisms and ageing, made by the individual contributors to the document, are compared. The numbers in the individual table fields refer to comments made by the evaluators, which are presented below the table. Mean level of coupling factor coincidence with ageing is defined in the column with the heading “Ave”, which was postulated on the base of four individual estimators. Finally, in the column with the heading “Dif”, inter-variability of four estimators is specified by means of simple classification (very small - small - medium - medium-high high).

Table 2: The results of comparison of connection strength between coupling factors and ageing phenomenon

Coupling factor/ mechanism	Strength of connection					
	INR	**CVNPP**	**ENEA**	**NRI**	**Ave**	**Dif**
Hardware based - design						
same physical appearance	insignific. (I1)	medium-weak (C1)	insignific.	medium-weak (N1)	weak	small
system layout/ configuration	medium (I2)	medium (C2)	relatively strong	rel.strong (N2)	medium-strong	small
same component internal parts	medium (I3)	strong (C3)	medium-weak	medium-weak (N3)	medium	medium-high
same maintenance/ test/ calibration	medium (I4)	medium-weak (C4)	medium	medium (N4)	medium	very small

Coupling factor/ mechanism	Strength of connection					
	INR	CVNPP	ENEA	NRI	Ave	Dif
characteristics						
Hardware based - manufacturing and installation quality						
manufacturing attributes	relatively strong (I5)	medium-weak (C5)	medium-weak	medium (N5)	medium	medium
construction/ installation attributes	medium-weak (I6)	medium (C6)	medium	medium-weak (N6)	medium	small
Operational based						
same operating staff	medium-weak (I7)	insignific. (C7)	medium-weak	insignific. (N7)	weak	small
same operating procedure	medium-weak (I8)	insignific. (C8)	medium-weak	medium-weak (N8)	medium-weak	very small
same maintenance/ test/ calibration schedule	medium-weak (I9)	insignific. (C9)	relatively strong	medium (N9)	no agreem.	high
same maintenance/ test/ calibration staff	medium (I10)	insignific. (C10)	relatively strong	medium (N10)	medium	medium
same maintenance/ test/ calibration procedures	medium (I11)	medium-weak (C11)	relatively strong	medium (N11)	medium	medium-high
Environmental based						
same plant location	medium (I12)	relatively strong (C12)	strong	medium (N12)	relatively strong	medium
same component location	relatively strong (I13)	relatively strong (C13)	strong	rel.strong (N13)	relatively strong	very small
internal environment/ working medium	strong (I14)	medium-weak (C14)	strong	rel.strong (N14)	relatively strong	medium

INR comments to interrelations between CCF individual coupling factors and ageing phenomenon:

(I1) - This factor is more connected to operating human errors and less to A_CCF.

(I2) - Wrong layout/configuration may results in high wear rate of a component category (example: bearing of the pumps/motors shift – the RMZ (Zero Power Multi-zone Reactor main circulating pumps) failed due to design error - wrong position; this situation was identified at preoperational tests and the pumps were relocated).

(I3) - Same internal parts represents a favorable condition for similar failure, for example, the main RMZ circulating pumps failed in the same mode after the same mission time (due to identical bearing of pumps shift weakening).

(I4) - Too high or too low force/torque specified as necessary and applied at maintenance operation/calibration/test may result in high wear rate of the pumps or motors, or may result in external/internal leaks at a variety of the circuit components.

(I5) - Improper selected materials give favorable conditions for A_CCF occurrence.

(I6) - The same construction/installation staff, construction/installation testing/verification procedure and construction/installation schedule can create conditions to induce similar degradations.

(I7) - The specified staff can be insufficiently skilled, insufficiently motivated, or without sufficient safety culture. These aspects are important both for CCF and A_CCF.

(I8) - The operating procedures are periodically reviewed. The same inadequate operating procedure is an important aspect for A_CCF.

(I9) - The same maintenance/ test/ calibration schedule is important for CCF/A_CCF.

(I10) - The specified staff can be insufficient skilled, insufficient motivated, or without sufficient safety culture. These aspects are important both for CCF and A_CCF.

(I11) - The operating procedures are periodically reviewed. The same inadequate maintenance/ test/ calibration procedure is an important aspect for A_CCF.

(I12) - This aspect is important for CCF, but can be important too for A_CCF. Relatively high frequency of humidity/flooding in plant area can induce multiple degradations.

(I13) - This aspect is important for CCF, but can be important too for A_CCF. (Example 1: The same location for two types of valves permitted a commission human error – the operator closed inadequate valve end blocked cooling flow for Kestner installation; Example 2: Humidity and low temperature affect all valves in same location; Example 3: An external leak into a room at NPP-Cernavoda affected "SLCD" detectors; Example 4: A variety of equipment located into a room heaving corrosive atmosphere can be simultaneous affected as electrical and I&C circuits/equipment of support systems.)

(I14) - The internal environment/working medium is very important for A_CCF (strong connection to A_CCF). It is one of the main factors that induce degradations in time (Example: The inadequate water chemistry for D_2O circuits (CANDU reactor) leads to accelerated corrosion of circuits components).

In addition, general comment was made to the list of coupling factors that evaluation of level of connection with ageing is fairly subjective. Indeed, this conclusion is right. Only additional more detailed analysis of current all along increasing volume of information about CCF events can make the conclusions about the subject of analysis more objective.

<u>CVNPP comments</u> to interrelations between CCF individual coupling factors and ageing phenomenon:

(C1) - Example: A number of identical 6 valves and one of it is manually tripped and isolated for maintenance and because of identical size/shape and similar position, the maintainer is working on control logic of another valve. **Most frequent on early stage of plant operation due to strong human aspect of this factor**. (NRI comment - this is good example of CCF potential, but not of a link between CCF and ageing).

(C2) - It was found decreasing with time, as the poor design configuration was detected quite early from operational experience. Still it is hard to decide if represents installation error (in this case belongs to coupling factor category *construction/ installation attributes*) or is the category under concern.

(C3) - Defective PRV diaphragm, pneumatic relay, 3C relay, fan belts can be seen as examples.

(C4) - This age dependency factor is from medium weak to insignificant because these types of events are happening almost constantly over time and a tendency of increasing CC failures can not be revealed.

(C5) - It may be difficult to detect such kind of dependency, as the manufacturer of components is not the same over equipment life.

(C6) - Later modifications perceived to slightly increase the connection under concern, as the component ages.

(C7) - Age dependency of these phenomena cannot be detected as it appears to happen with approx. the same frequency over time.

(C8) - No evidence of dependency with component ageing.

(C9) - No evidence of dependency with component ageing.

(C10) - No evidence of dependency with component ageing.

(C11) - Expected to decrease over time since the procedures are discussed and common understanding of steps is performed (pre job briefing, independent maintenance procedure check). No evidence of dependency with component ageing.

(C12) - Since this factor refer to environmental stresses, it is recognized that the weather change poses a significant challenge to plant operation mostly in late years.

(C13) - Effects like pipe whip or high energy line break are considered in late phase of plant operation.

(C14) - The occurrence of such phenomena was found equally happening in early time operation as it is in recent time.

<u>NRI comments</u> to interrelations between CCF individual coupling factors and ageing phenomenon:

(N1) - For the components with significantly different physical appearance, connection of this factor with ageing may be seen as negligible. However, if there is some level of similarity, it may be further increased by ageing effects, because the specific, unique features of the individual components may gradually get disappeared in the process of ageing (decreased readability of component identifiers, loss of identification elements etc.).

(N2) - In PSA model, this case refers to connection of formally separated components in higher level of system function logic. If there is also some hardware component the core of this higher level connection, it can be exposed to some sort of ageing mechanisms. Any potential increasing of failure rate of this higher level component (if it is not modeled in PSA) due to ageing can be seen as increasing of common cause failure potential. “Tiny” I&C component, not modeled in PSA, having impact on availability of same type components in several redundant trains of the system, can be seen as very good example.

(N3) - The same type of component internal parts does not belong to CCF factors with significant connection to ageing potential. In this case, the strength of CCF-ageing link is usually superseded with the factor “the same manufacturer”. Still, even a common construction principle may represent a kind of CCF failure potential increasing in time due to effects of ageing.

(N4) - One of common general maintenance goals is prevention of effects of known and expected-to-occur ageing mechanisms. Since the maintenance strategy principles are usually built in such a way that there are dependences and correlations in planning, organization and way of carrying out the individual maintenance acts for various types of components, there is some possibility that ageing mechanisms may not be addressed adequately not only for one, but for all components forming some CCF group in PSA model.

(N5) - “The same manufacturer” factor overlaps, to some extent, with the “the same internal parts” factor. The production quality (by the same manufacturer) is strongly determined by quality assurance principles exerted during production and ageing phenomena treatment may be seen as one of them. In case that these quality principles are deficient from ageing impacts point of view, ageing may take place, with higher probability, in operational life of major part of products/components, including mutually redundant components of the same type forming PSA groups in plant PSA models.

(N6) - Some potential exists for latent effect of hidden impact of wrong equipment installation for a long time period and strengthening of it in interaction with ageing mechanisms, such potential was evaluated as non-negligible, but relatively weak.

(N7) - CCF impacts of plant equipment operation with the same staff can be seen as strong cause-based connection between repeated human errors and consequences of making them. Since the strength of failure cause is usually fairly high in human induced failure, the effect of human error is mostly immediate. Thus, the potential for surviving of consequences of failed activity of the same operational team in latent status for such a long time, the effects could interfere with ageing mechanisms, is very small. In addition, the typical ageing effects develop during a relatively long time period; the operational team may be subjects of changes within.

(N8) - The influence of the same operational procedures was evaluated as higher than the same team influence, because the changes in content of procedures are usually smaller and less frequent than in operational team. As a consequence, accumulation of procedure negative influences and interaction of them with ageing mechanisms may have better chance to take place for a long time period.

(N9) - For a number of safety important components, latent effects of not optimum maintenance, cumulated and interfering with real ageing impacts in future are stronger than effects of operational problems. If maintenance strategy is deficient in some way, there is a quite real chance that undesirable effects will repeatedly take place during periodically performed maintenance acts, potentially contributing to ageing. These effects may interact with „real“ ageing mechanisms directly or they may initiate and strengthen the impact of these mechanisms.

(N10) - The influence of this factor is very specific and variable, tightly connected with the frequency of changes in the maintenance/ test/ calibration staff (which is given by plant human resources politics, including level of outsourcing and safety culture of external contractors, and can be fairly different among the plants). In the operation of plants with relatively low staff fluctuation, the factor may be quite important, because the maintenance/ test/calibration style may become loaded with a kind of negative stereotypes, with cumulating effects contributing to ageing of various components gathered in the PSA CCF groups.

(N11) - A general conclusion similar to the case of the factor „same maintenance/ test/ calibration schedule “takes place. The same maintenance/ test/ calibration procedure is a factor of long term influence, but, at the same time, a factor of not that strong influence proven.

(N12) - The same plant location means the same location for all components, implying similar impact of external environmental characteristics, which define, to some extent, ageing potential. The strength of this factor is similar and the factor may be seen as relatively important for most of components of the technology under concern.

(N13) - Location „face to face“ implies common impact of a number of negative influences challenging component status during the whole component life period. In case that these influences generate common cause failure potential, CCF vulnerability will gradually increase as a consequence of negative impacts accumulation.

(N14) - The same conclusions as those made for the other factors from this group hold. Usually, there is a very intensive contact between internal environment and the component under concern. The negative consequences may be more difficult to be observed in this case. On the other hand, the spectrum of negative influences should not be that wide.

The following general conclusions can be made on the base of comparison made in Table 2:

- the interrelation between common cause failure potential represented by individual CCF coupling factors and ageing phenomenon was estimated as fairly strong, both for total, summarized CCF potential, and for the individual coupling factors, it may be pointed out that, in integrated opinion (see the column with a heading “Ave” in the table), the connection was never characterized as “irrelevant” and there are only two cases, it was classified as “weak”

- the level of agreement among all four participants fulfilling the questionnaire was presented as pretty good (see the column with a heading “Dif” in the table), with one exception concerning a group of CCF coupling factors connected with maintenance, where the agreement among evaluators was pretty bad
- each of four groups of CCF coupling factors was found as being of at least medium importance regarding connection with ageing, the dominating group with respect to ageing is environmental based factors, the coupling factors from this group could be prioritized in selection for more detailed analysis, if such analysis would have be planned in future
- among four participants in the study, there was no evaluator with too distant evaluations systematically made (overly optimistic or pessimistic), some level of conservativeness can be seen in ENEA evaluations, the evaluations of remaining three participants are quite balanced regarding conservativeness level
- same physical appearance and same operating staff are two factors evaluated as with weak connection to ageing phenomena (with small variability of estimates)
- all environmental based coupling factors were evaluated as relatively strong in connection to ageing, in case of same component location factor with very small variability of the individual estimates.

4.2 Individual impact of CCF defense and prevention elements on strength of the links between coupling factors and ageing phenomenon

This section of the questionnaire was focused on influence of CCF defense and prevention measures on CCF coupling factors connection with ageing. The results of fulfilling of second part of the questionnaire are compared and evaluated. Tables fulfilled by the individual participants are presented as Table 3 - Table 6. The structure of the tables and the formalisms used are the same as described in Section 3.3. Comments to evaluations presented in tables provided by INR and NRI specialists can be found below the corresponding tables.

For all individual fields defined in Tables 3-6, the final Table 7 provides integrated (averaged) estimations based on previous tables and developed in similar way as averaged estimations in the column “Ave” in Table 2. The numbers in the individual fields of Table 7 characterize level of agreement in similar way as shadowed fields in the column “Dif” in Table 2 (1 = very small, 2 = small, 3 = medium, 4 = medium-high, 5 = high).

Table 3: Confrontation of CCF defense and prevention elements with connection of the individual factors of CCF potential with ageing phenomena evaluated by CVNPP

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance										
system layout/ configuration										
same component internal parts										

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
same maintenance/ test/ calibration attributes										
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes										
construction/ installation attributes										
Operational based										
same operating staff										
same operating procedure										
same maintenance/ test/ calibration schedule										
same maintenance/ test/ calibration staff										
same maintenance/ test/ calibration procedures										
Environmental based										
same plant location										
same component location										
internal environment/ working medium										

Table 4: Confrontation of CCF defense and prevention elements with connection of the individual factors of CCF potential with ageing phenomena evaluated by INR

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance										
system layout/ configuration				**I1**						
same component internal parts		**I2**	**I3**	**I4**	**I5**	**I6**			**I7**	
same maintenance/ test/ calibration attributes		**I8**	**I9**	**I10**					**I11**	
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes		**I12**		**I13**	**I14**				**I15**	
construction/ installation attributes				**I16**						
Operational based										

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
same operating staff				I17						
same operating procedure				I18						
same maintenance/ test/ calibration schedule				I19					I20	
same maintenance/ test/ calibration staff		I21		I22						
same maintenance/ test/ calibration procedures		I23	I24							
Environmental based										
same plant location		I25			I26				I27	
same component location		I28			I29				I30	
internal environment/ working medium	S	I31	I32						I33	

<u>INR comments</u> to interactions of CCF defense and prevention elements with ageing mechanisms are presented in the list below; only the impacts evaluated as medium, medium-high and high are commented there:

I1: The diversity principles (D_1, D_2, D_3) and barriers (B_1, B_2) can decrease the influence of the specified coupling factor (the main RMZ circulating pumps were located in wrong position due to design requirements and they failed to perform NPSH condition; this situation was identified and solved at the preoperational tests (the pumps were relocated), so the system layout is a very important factor for CCF_and the staff diversity (D_3) is a very important contra-measure)

I2, I3, I4: The diversity principles (D_1, D_2, D_3) can decrease the influence of specified coupling factor and will weakening the link between CCF and ageing. (RMZ circulating pumps failed in same failure type, because of identical weakening of pumps bearing shift);

I5, I6: The barriers (B_1, B_2, B_3) can decrease the influence of specified coupling factor (for example, the spatial separation in case of control logic devices, located in different panels/boxes, decreases the occurrence of CCF/A_CCF events - ADAMS electronic modules in non-reactor installations analyzed);

I7: The different (higher) frequency for maintenance activities of circuit breakers contacts (contacts cleaning) can decrease the likelihood of A_CCF;

I8, I9, I10: The diversity principles (D_1, D_2, D_3) can have a strong influence in decreasing of specified coupling factor (I&C equipment from different systems may have the same calibration/ testing attributes, but having different operational modes and conditions, various internal parts and operating principles have different potential for CCF events);

I11: The probability that an operator will perform a wrong maintenance action will change/ decrease if the maintenance policy is changed.

I12, I13: The diversity principles (D_1, D_3) can decrease the influence of specified coupling factor (components from redundant measure/surveillance line have the same manufacturing attributes, but different operational modes, which give them different potential for CCF occurrence; staff diversity may change also the potential for failure). The example is applicable to CANDU, TRIGA, RMZ reactors.

I14: Spatial separation of components with similar manufacturing attributes can decrease the influence of specified coupling factor (ex: similar valves located in different systems)

I15: The changes in maintenance policy can be adequate means for A_CCF potential limitation.

I16: Some deficiencies of construction/ installation attributes can be observed and repaired during preoperational (commissioning) tests when different teams are used.

I17: Using different operational teams for different levels/category of operations (CANDU reactor) will contra-measure the probability to make the same mistake when the same team is used. Still, not all the teams have the same level of competences, so this preventive factor will not compensate totally the coupling factor.

I18, I19: Using staff diversity the coupling factor will be weakened. Different teams can have different levels of competences for different operations, even using the same procedure and having the same test/ maintenance schedule.

I20: Changes in maintenance policy can significantly influence the coupling factor.

I21: Functional diversity can influence the coupling factor effect; a possible error will propagate less easily in case of functional diversity of equipments.

I22: Diversity staff principle will contra-measure the effect of possible errors when the same calibration/test team is used.

I23, I24: The diversity principles (D_1, D_2) can decrease the influence of specified coupling factor (Example1: Using two radiation detector type in redundant lines to explore radiation field in the same location will decrease the potential for CCF; Example 2: functional/equipment diversity for SCRAM signal lines in TRIGA-SSR and RMZ reactors, Example 3: functional/equipment diversity for safety shutdown systems (CANDU reactor);

I25, I28: Diversity principles produce positive results regarding safety. Functional diversity will decrease (contra-measure), in principle, the effect of potential external events, as the effect of aggressive environment.

I26, I29: Spatial separation may impact the factors of potential external events, as the effect of aggressive internal environment.

I27, I30: Changes in maintenance policy can overcome the effect of potential external events, as the effect of aggressive internal environment.

I31, I32: Functional and design diversity will contra-measure, in principle, the effect of aggressive working medium.

I33: Changes in maintenance policy can overcome the effect of aggressive working medium.

Additional specific INR comment was also made to the CCF preventive measure represented with last column of the table (with the heading “Z”). From INR point of view, additional level of redundancy is not enough feasible solution, it can increase the coupling factors potential and it is not efficient from economical point of view. The additional level of redundancy usually increase the probability of CCF events, and with ageing CCF, the level of risk is increasing even more. (This may be interesting view of the problem, which could originate another discussion in future).

Table 5: Confrontation of CCF defense and prevention elements with connection of the individual factors of CCF potential with ageing phenomena evaluated by ENEA

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance										
system layout/ configuration										
same component internal parts										

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
same maintenance/ test/ calibration attributes										
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes										
construction/ installation attributes										
Operational based										
same operating staff										
same operating procedure										
same maintenance/ test/ calibration schedule										
same maintenance/ test/ calibration staff										
same maintenance/ test/ calibration procedures										
Environmental based										
same plant location										
same component location										
internal environment/ working medium										

Table 6: Confrontation of CCF defense and prevention elements with connection of the individual factors of CCF potential with ageing phenomena evaluated by NRI

CCF occurrence factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance		N3	N3	N4	N14	N18	N22	N26	N27	N31
system layout/ configuration		N5	N5	N12	N15	N20	N22	N24	N28	N32
same component internal parts		N5	N5	N12	N15	N19	N22	N26	N28	N32
same maintenance/ test/ calibration attributes		N6	N6	N12	N15	N18	N22	N26	N29	N32
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes		N7	N7	N12	N15	N19	N22	N26	N28	N32
construction/ installation attributes		N7	N7	N12	N15	N19	N22	N26	N28	N32
Operational based										
same operating staff		N8	N8	N8	N8	N8	N8	N8	N8	N8

CCF occurrence factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
same operating procedure		N9	N9	N12	N15	N19	N23	N26	N28	N32
same maintenance/ test/ calibration schedule		N10	N10	N12	N16	N19	N23	N26	N30	N32
same maintenance/ test/ calibration staff		N10	N10	N13	N15	N19	N23	N26	N30	N32
same maintenance/ test/ calibration procedures		N10	N10	N12	N15	N19	N23	N26	N30	N32
Environmental based										
same plant location		N11	N11	N12	N15	N19	N22	N26	N28	N32
same component location		N11	N11	N12	N17	N21	N22	N26	N28	N32
internal environment/ working medium		N11	N11	N12	N17	N19	N22	N25	N28	N32

NRI comments to interactions of CCF defense and prevention elements with ageing mechanisms are presented in the list below:

N1: It should be pointed out that the goal of evaluation (reflected in color coding of the individual fields in the table) **is not** to measure the strength of prevention factor, rather it is to specify the influence of it on **connection** between common cause failures and ageing approximately.

N2: A logical consequence of Note 1 may be that, although all preventive factors (as verified by practice) should have a positive impact on CCF potential (decreasing it), a strength of CCF-ageing connection may even increase due to impact of the given prevention factor, theoretically. Still, decreasing of strength of this relationship may be to prevail significantly in practice.

N3: Functional or design diversity usually brings big differences in components appearance. Those specific features of every different component in the group of components of the same type, which may vanish during the process of component ageing, may belong to key elements of between-the-components differentiation process. Thus, the strength of CCF and ageing relationship may be significantly weakened by application of diversity principles.

N4: Application of diversity in selection of operational or maintenance staff leads only to partial elimination of the link between CCF potential and ageing. If concrete members of plant staff are allocated to carry out preventive as well as corrective maintenance of technology segment (one branch of a system with several redundant branches), the potential for erroneous interchange is very small. However, as it can be seen in plants operational history, the most frequent and important cases of undesirable interchanges of this type are connected with the status after changes made in plant staff or with delegation of external contractors staff for some one-time maintenance act. However, the category of these potentially important cases is estimated as not significantly influenced with application of diversification principles.

N5: For these factors, diversity essentially eliminates CCF potential as a whole, thus; as a consequence, the link between CCF and ageing is also weakened.

N6: The impact of diversity is twofold. Developing of differences between the individual system branches initiates requirements for at least partially different maintenance acts and strategy, making the potential for repeated human failures lower (including failures with cumulative effects important from ageing point of view). In addition, diversity principles application may result in a need to call for different specialists to maintain the individual system branches, what may lead to further limitation of dependent failures potential.

N7: Application of diversity principle may have obvious straightforward effect regarding dependent failures occurring due to component production by the same manufacturer, or, in broader sense, elimination of CCF by incorporation of different contractors into the process of component production and installation. However, since the link of these CCF factors with ageing is relatively weak, the impact of prevention is weak too.

N8: The influence of this factor was already rated by the lowest degree in Table 1. Since the prevention factors usually further decrease CCF potential, the lowest possible degree is kept for all combinations of this factor with the individual prevention factors.

N9: In general, diversity application leads (as a part of pre-defined process of management of change) to reflection of character and needs of new diversified elements of the individual system branches in operational procedures and, consequently, to decreasing of CCF potential connected with using of procedures and human errors in general, including connection with ageing phenomenon. Still, the records taken from operational experience show frequently that those serious deficiencies in procedures, which may leas as far as to increasing of human failure potential, are often not concrete actual technical drawbacks (mostly eliminated during the process of procedures verification and validation), but they are linked with general features of quality of the process of development plant documentation and keeping it updated (including emphasize put upon procedures ergonomics), which may not be significantly impacted with newly adopted component diversity principles. For that reason, CCF-ageing interaction potential decreasing was evaluated as of low significance.

N10: For the factors belonging to maintenance area, application of diversity principles usually initiates significant decreasing of CCF potential in all directions - planning, staffing as well as procedural support.

N11: In combination with similar environment, the application of diversity principles produces positive results regarding safety. Still, a general character of non-standard plant states under concern generated with environmental influences leads to the conclusion, that significant part of authentic CCF potential remains in place. The total effect of functional diversity is usually more significant, as long as it is related to application of different physical principles and phenomena (having different connections to inherent effects of the environment). As soon as diversity is limited to using of different components, the system as a whole remains more vulnerable.

N12: Intentional diversification in plant and contractors staff approaches to installation, operational control and maintenance of component has only small influence on factors connected with design and manufacturing (treated separately from the factors connected with component life in plant location). Similarly, the influence is low also for a number of other factors connected with procedural support (differences in approaches of different teams to operation and maintenance do not necessarily lead to changes in procedures content) or external conditions of component operation.

N13: These elements of CCF potential are influenced highly by using of diversity principles, because they can be seen just as targets of diversity application.

N14: The most critical impact of the factor is creation of potential for interchange of the individual system branches. A spatial separation eliminates the influence of this factor to significant extent.

N15: Spatial separation does not have any impact on these factors evidently.

N16: Spatial separation of one given component from the rest of components in CCF group may lead to involvement of diversity elements into the maintenance style.

N17: The influence of the factor should be high, because, as a matter of fact, this is directly a kind of phenomenon, spatial separation is usually oriented to. Still, the influence is not extremely high in practice, because the ideas of spatial separation normally have to respect the limitations of current (other) components arrangement in plant location. In addition to external environmental factors, operational changes connected with spatial separation may impact the factors of internal environment, to some extent.

N18: Creation of physical barrier may partially limit, although still not absolutely eliminate, the possibility of component interchange due to gradual degradation of identification elements. Similarly, there is certain, but not sufficiently conclusive influence on similar maintenance attributes.

N19: From point of view of the given factors, component isolation by creation of physical barriers does not have any big of significant measure. It can be supposed that physical barriers are built in such a way; they do not interfere with (required) operational characteristics of the component and do not cause basic problems for components maintenance. In accordance with current practice, the barriers can be seen as elements of prevention against external environmental effects much more than internal (working medium) effects prevention.

N20: The strength of the CCF factor (and relation to ageing) is given by internal characteristics of system operation logic and system structure. These attributes are not influenced by providing physical barriers between the components belonging to individual system trains.

N21: Similarly to spatial separation, the prevention factor belongs to the basic means of elimination of the given factor influence. The estimated strength of prevention is slightly lower than in case of physical separation, because the factor is oriented only to selected (usually the most important) concrete threats.

N22: This very specific element of prevention impacts only the factors imminently connected with operation and maintenance practice.

N23: The factor has significant influence on instantaneous potential of CCF occurrence due to human or organizational failures during maintenance. However, the factors important from point of view of ageing are typical with long term devaluation of maintenance quality, where the interference with the given prevention factor is low.

N24: Elimination of cross-ties between redundant trains will eliminate some postulated CCFs, although it may lead to occurrence of new ones, connected with human or organizational factors, for example. Altogether, the estimated effect regarding connection with ageing should be positive.

N25: Removing of cross-ties may reduce, to some extent, possible negative influence of transported medium. Still, such impact will persist and the effects of it will cumulate, but will not affect particularly vulnerable piping segments areas (cross-ties). Thus, CCF/ ageing connection may be significantly eliminated this way.

N26: Aside from two significantly influenced factors in a way described in previous two notes, the impact of this rather specific prevention means is small.

N27: From point of view of accumulation of ageing related effects, the factor has negligible impact. In fact, it can be seen as a kind of debatable prevention, where the CCF potential may be even increased. Spreading of tests and maintenance of the individual, mutually redundant system branches over a broader time period may increase probability of wrong identification of components (with increasing of memory demands and weigh of some organizational factors).

N28: Different way of maintenance organization does not have any connection with the given factors, thus, it does not impact the strength of factors connection with ageing.

N29: Although the given factor is, in the role of CCF potential contributor, related to maintenance, just the changes of individual maintenance activities timing do not have measurable impact, provided that the technical essence (defining the links to CCF potential) is going to remain the same.

N30: The changes in maintenance technical character can also significantly influence the timing of it so that the impact of prevention factor is pretty high here. Some kind of balanced spreading of maintenance acts over all system operation period may have also secondary effects regarding diversification of maintenance staff (time separation of maintenance can introduce other maintenance specialists or teams into the process). On the other hand, the content of maintenance procedures (important from point of view of CCF) is not considered to be strongly touched with this prevention factor.

N31: Increasing of redundancy level generally does not solve the problem of possible convergence of component appearance due to ageing.

N32: Increasing of redundancy level has some impact on most of CCF coupling factors. First, partial application of diversity principles may be expected being connected with any new redundancy level, having some impact on most of factors related to design, component location, installation, operation and maintenance. In addition, the link between CCF potential and ageing is attacked, because the new redundancy level is usually added in later period of plant life, with some ageing symptoms already developed in the other system branches, to a significant difference from the newly originated branch.

Table 7: Integrated results of analysis of impact of CCF defense and prevention elements on connection of the individual factors representing CCF potential with ageing phenomena

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance		3	3	1	3	3	1	1	2	2
system layout/ configuration		3	2	2	2	3	4	3	4	3
same component internal parts		3	2	3	3	3	2	1	3	2
same maintenance/ test/ calibration attributes		3	3	2	3	3	3	2	3	3
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes		3	3	3	3	2	2	2	3	2
construction/ installation attributes		3	3	4	3	3	3	4	4	3
Operational based										
same operating staff		2	2	3	2	1	1	1	2	1
same operating procedure		2	2	3	2	2	2	2	2	2
same maintenance/ test/ calibration schedule		4	4	4	3	3	3	3	4	3
same maintenance/ test/ calibration staff		4	4	3	3	3	3	3	3	2
same maintenance/ test/ calibration procedures		3	3	2	3	3	3	3	2	3
Environmental based										
same plant location		2	2	3	3	3	3	2	3	3
same component location		3	3	3	3	2	3	3	3	3
internal environment/ working medium		3	3	2	2	3	3	4	3	2

Table 7 represents average general opinion about the subject of analysis. In addition, was found useful to develop similar table representing a kind of conservative evaluation, where the most conservative opinion among all four participants is present. The idea behind this approach is that small impact of CCF defense and prevention strategies presented as opinion may be a consequence of not very good identification of cases with influence proven, but high impact is almost always based on "something real". Table 8 represents application of this principle. The estimators of variability presented in Table 8 were copied from Table 7.

Table 8: Conservative results of analysis of impact of CCF defense and prevention elements on connection of the individual factors representing CCF potential with ageing phenomena

CCF coupling factor	N	D_1	D_2	D_3	B_1	B_2	B_3	B_4	U	Z
Hardware based - hardware design										
same physical appearance		3	3	1	3	3	1	1	2	2
system layout/ configuration		3	2	2	2	3	4	3	4	3
same component internal parts		3	2	3	3	3	2	1	3	2
same maintenance/ test/ calibration attributes		3	3	2	3	3	3	2	3	3
Hardware based - hardware quality (manufacturing and installation)										
manufacturing attributes		3	3	3	3	2	2	2	3	2
construction/ installation attributes		3	3	4	3	3	3	4	4	3
Operational based										
same operating staff		2	2	3	2	1	1	1	2	1
same operating procedure		2	2	3	2	2	2	2	2	2
same maintenance/ test/ calibration schedule		4	4	4	3	3	3	3	4	3
same maintenance/ test/ calibration staff		4	4	3	3	3	3	3	3	2
same maintenance/ test/ calibration procedures		3	3	2	3	3	3	3	2	3
Environmental based										
same plant location		2	2	3	3	3	3	2	3	3
same component location		3	3	3	3	2	3	3	3	3
internal environment/ working medium		3	3	2	2	3	3	4	3	2

The following general conclusions can be made on the base of evaluations presented in Table 7 and Table 8:

- There is relatively small number of cases; the effect of concrete CCF prevention strategy on CCF-ageing link was evaluated as negligible on the base of opinion of all four evaluators.
- Most of evaluated combinations of prevention strategy and CCF coupling factors-ageing links obtained “weak” grade, but significant number of combinations were evaluated as “medium” and a couple of them even higher
- The CCF prevention strategies based on application of diversity principles were found as significantly breaking the link between CCF potential and ageing, much more than the remaining classes of prevention strategies.
- The level of subjectivity and corresponding level of variability of estimations is generally higher than in case of directly estimated CCF coupling factors versus ageing coincidence (Table 2), but it is still evaluated as “medium” only in most cases. Some cases with high variability of evaluators’ opinion are mostly connected, similarly to “direct” estimation of CCF coupling factors connection with ageing, with those coupling factors, which are related to maintenance.
- The “conservative” estimates (Table 8) show that at least one evaluator find some reason to classify the impact of CCF prevention strategies on CCF-ageing link as medium-high in many cases. This fact further supports the conclusion about importance of CCF prevention strategies.

4.3 Overall impact of CCF prevention elements on strength of the links between coupling factors and ageing phenomenon

In previous section, the results focused on influence individual CCF defense and prevention measures on CCF coupling factors connection with ageing taken from fulfilled questionnaires were studied. The aim of this section is to summarize the results in two ways:

- to get overall impact of prevention factors on the individual links between individual CCF coupling factors and ageing
- to get overall impact of individual prevention factors over all CCF coupling factors links with ageing.

Tables 7, 8 were used for analysis in the form similar to Table 2. In these tables, evaluations provided with all participants will be given, supplemented with summarized (averaged) estimations and specification of variability of estimates.

Table 9: Summary on influence of CCF prevention means on the links between CCF potential and ageing

Prevention factor	Strength of effect					
	INR	CVNPP	ENEA	NRI	Ave	Dif
Application of diversity principles						
functional diversity	I1	**C1**		N1		small
equipment design diversity	I2			N2		small
human factor related diversity	I3			N3		medium

Prevention factor	Strength of effect					
	INR	CVNPP	ENEA	NRI	Ave	Dif
Physical or functional barriers						
spatial separation	**I4**			N4		**medium**
physical protection - barrier	**I5**			**N5**		**medium-high**
interlocks	**I6**			**N6**		**medium-high**
removal of, or administrative control on, cross-ties	**I7**			**N7**		**high**
Testing and maintenance policy						
staggered testing and maintenance	**I8**			**N8**		**medium**
Up-date of redundancy strategy						
additional redundancy	**I9**	**C2**		**N9**		**medium**

Some conclusions made on the base of Table 9 are logically close to the conclusions coming from tables 7, 8. In addition, it can be summarized that:

- prevention strategies based on application of diversity principle were evaluated as most important with all evaluators
- some difference in opinions of individual evaluators can be seen directly from the table - the estimations of prevention strategies impact made by ENEA are pretty high, the estimations made by INR relatively low, CVNPP and NRI, as representatives of subjects with nuclear power plant experience are in the middle of the pool
- the conclusions regarding CCF prevention strategies based on physical on functional barriers are typical with high level of variability, on the other hand, there is very good agreement in estimation of (high) impact of prevention strategies based on diversity.

CVNPP comments to the evaluations in the table

C1: The principles like diversity, redundancy, 2 out of 3 channel trip criteria, channel independence (spatial and power supply) are imbedded into plant project design and covers all the safety and safety support systems. Therefore the preventive factor called diversity (functional and equipment design) cannot be evaluated more than it was in original design.

C2: No such measures have been employed up to now.

INR comments to the evaluations in the table

I1: This measure can decrease the environmental effects ageing related impacts, and some of the design based coupling factors.

I2: Very important as counter-measure in case of same component internal parts.

I3: Important for several CCF coupling factors operational based, primarily related to maintenance activities.

I4: Spatial separation can reduce the effects of external events or aggressive environment.

I5: This factor has low importance for ageing CCF.

I6: Low importance for ageing potential.

I7: Low importance.

I8: Strong importance for counter-measure the same maintenance/test/calibration schedule, and important for decreasing the environmental effects ageing related impacts.

I9: This measure was considered as having low importance.

NRI comments to the evaluations in the table

N1: This prevention factor is able to influence, in substance, almost all kinds of CCF potential contributions in their connection with ageing. Although primary oriented to design attributes, it can affect human part of operational process, as well, the same way as to decrease the environmental effects ageing related impacts.

N2: The factor is typical with similar strength of effect as the functional diversity, slightly lower in case of some CCF factors.

N3: May be of some importance for CCF-ageing links only for a several CCF coupling factors primarily related to maintenance.

N4: The influence of the factor varies significantly.

N5: Similar conclusions as for spatial separation holds, the total effect is somewhat lower.

N6: This factor is of low importance for CCF connection with ageing. This conclusion is logical, because the effect of the factor is mostly immediate.

N7: More significant for two factors only, but these factors are fairly important form point of view of CCF connection with ageing phenomena (system layout/configuration, internal environment).

N8: Stronger importance for two specific factors only, the total effect on the CCF-aging link is tame due to low level of cumulation of negative impacts in a long term.

N9: The influence is frequently indirect, but potentially significant regarding most of CCF mechanisms and connection of them with ageing phenomena.

Table 10: Summary on importance of CCF prevention means for weakening of the links between CCF potential and ageing (represented with specific coupling factors)

Coupling factor/ mechanism	Strength of connection					
	INR	CVNPP	ENEA	NRI	Ave	Dif
Hardware based - design						
same physical appearance						**small**
system layout/ configuration						**small**
same component internal parts						**medium**
same maintenance/ test/ calibration characteristics						**small**

Coupling factor/ mechanism	Strength of connection					
	INR	CVNPP	ENEA	NRI	Ave	Dif
Hardware based - manufacturing and installation quality						
manufacturing attributes						**small**
construction/ installation attributes						**medium-high**
Operational based						
same operating staff						**small**
same operating procedure						**small**
same maintenance/ test/ calibration schedule						**high**
same maintenance/ test/ calibration staff						**high**
same maintenance/ test/ calibration procedures						**high**
Environmental based						
same plant location						**medium-high**
same component location						**medium**
internal environment/ working medium						**medium**

The evaluations presented in Table 10 support some conclusions made based on information from tables 2, 7, 8, and 9.

5. SUMMARY AND CONCLUSIONS

The purpose of this section is to make some final statements to the subject of analysis. This will be done by generalization of some ideas resulting from the results of concrete evaluations presented in previous sections, taking into consideration last part of the questionnaire devoted to more general aspects of CCF-ageing theme.

<u>Conclusion 1</u>

In the discussion among project participants, it was emphasized that, in general, **comparison of strength of CCF-ageing relation for the individual CCF coupling factors is <u>reasonable and useful</u>**. However, **under current circumstances, such analysis is connected with large deal of <u>subjectivity and uncertainty</u>.** That's why **it would be useful to organize <u>broader forum on this subject</u> with more opinions coming from bigger volume of supporting information**. It looks like **CCF-ageing relation is the topic for future studies**, because **<u>ageing</u> is expected as being <u>important</u>** point of both deterministic and probabilistic, both qualitative and quantitative safety studies **<u>in future</u>** as soon as many plants will continue operation in late part of lifetime or even extended lifetime.

<u>Conclusion 2</u>

In concrete results of analysis presented in Table 2, the **<u>interrelations</u>** between common cause failure potential represented by **individual CCF coupling factors** and **ageing** phenomenon were estimated as **<u>fairly strong</u>**, both for total, summarized CCF potential, and for the individual coupling factors.

This is important conclusion which also may result in recommendation to continue in this kind of analysis. The current analysis may be extended and refined in a couple of ways:

- organizing (much) broader forum for analysis
- using new, up-dated set of common cause failure coupling factors and (partially) new methodology for comparison.

<u>Conclusion 3</u>

It seems that although there is definitely some potential for further elaboration of both analysis methods and the set of CCF coupling factors, **the major potential for continuation in analysis and obtaining more representative results is in <u>extending of information sources</u>**. There are **many PSA studies** around the world supported with plant specific data collection, including CCF events, which could be used, together with even more operational experience gathered as a part of **nuclear power plants operation feedback processes**, as very useful input for the kind of reasoning demonstrated in this report.

An important subject of possible continuation of CCF-ageing relation analysis is plant specific information. In general, specific collection and selection of CCF events has become integral part of reliability and safety oriented data collection in nuclear facilities - power plants, research reactors etc. This is very important aspect, because as soon as there is plant specific information about CCF available, the strength of CCF-ageing relation may be further analyzed.

Most of project participants with potential for specific data collection provided samples of data describing CCF events from own operational history. The data from NRI were presented in Section 3, Table 5 in [5]. In similar form, two new samples were developed by INR and CVNPP, which are presented in Table 11 (NPP Cernavoda sample) and Table 12 (INR sample). The basic conclusion that can be made based on the operational experience is that common cause failures happen during operation of nuclear technology and there is some definitely non-negligible possibility that they are related to ageing.

The information provided with NPP Cernavoda includes operational CCF events with possible (a priori not required) ageing relation, that's why strength of such relation is specially coded in last column of Table 11. To some difference, the events provided with INR were a priori selected to have CCF origin and some ageing relation too so that additional color coding is not used in Table 12.

Table 11: Sample of common cause failure events in NPP Cernavoda operational experience from point of view of relation to ageing phenomenon

Event description	Risk and CCF related impact	Event relation to ageing
Partial opening during test of one motorized valve. Investigations extended to the rest in the set found conservant (grease) on actuator limit switch from manufacturer.	Possible unavailability of one of special safety system.	Procedure lapse, not directed to ageing
Isolation supposed by maintenance activity on Unit 1 Pump 2 affects also operation of similar Pump 2 of Unit 2, these pumps being in one pit.	Degraded function of similar pump of other unit in case of common mode events. The other trains, respectively Pump 1 of Unit 1 and Pump 1 of Unit 2 still available.	The principle of spatial separation is questioned, not directed to ageing.
The valves controlling the level in Steam Generators in emergency situation was found to have the seat for impulse air of pneumatic relay excessively worn.	Degraded function of boiler level control in emergency situation. CCF modeled in PSA also.	Probable link to ageing, this event is possible to be time dependent.
The valves controlling the level in Steam Generators in emergency situation was found to have failed PRV diaphragm.	Degraded function of boiler level control in emergency situation. CCF modeled in PSA also.	Event proven link to ageing.
Ageing of wall pass-trough insulation for both 110kV buses of Station A.	CCF modeled in PSA, degraded function of 110kV station to feed the plant internal services.	Event proven link to ageing.
Air tanks and related piping corresponding to the four Stand by Diesels on starting air system was found with rust and debris, impacting thus the requirement to start.	Important in failure to start events of in case of loss of normal power supply.	Manufacturing defects, lack of commissioning procedure related to the checking of clean state. No link to ageing.

Event description	Risk and CCF related impact	Event relation to ageing
Periodical failure (found with the testing occasion) of the downstream check valves related to the four trains of back up cooling pumps	The event has a low non negligible importance because of multiple alternate cooling systems which are available and ready to act before this system.	Design or installation failure in isometric of the common discharge header which generates water hammer in the backseat of the flapper arm.

Table 12: Sample of common cause failure events in INR operational experience from point of view of relation to ageing phenomenon

Event description	Risk and CCF related impact	Event relation to ageing
Ageing of protection discharges from redundant lines of high voltages (220KV)	Ageing of protection discharges from redundant lines of high voltages leads to putt to ground of these lines and loss of power supply system (support system from TRIGA reactor).	Ageing of dischargers (degradation of internal components) and inadequate maintenance.
Ageing/ inadequate quality of oil of the high voltage transformers (220KV/6KV)	The quality degradation of oil transformers can determine loss of high voltage supply lines (loss of power supply –support system for TRIGA reactor)	Ageing / inadequate maintenance.
Erosion of cables insulation	Loss of electric power supply and I&C components common cause failures	Clear connection to ageing.
TRIGA secondary circuit - the valves bodies are corroded, do not seal anymore and cannot be operated	Improper operation of valves results in a reduced flow through the system which was detected by the increasing temperature in primary circuit.	Wear and erosion processes have as effects the thinning of walls until leakage occurs. Corrosion phenomena can make the valve to operate with difficulty. Event was caused by ageing/ inadequate maintenance.
TRIGA secondary circuit - pipes breakages - the underground and external pipes are very corroded	Large breaks lead to harsh environment and flood with consequential failures of multiple equipment. Wall thinning and cracking are incipient failures, in time could lead to external leaks.	Corrosion-erosion may result in pipe wall thinning which compromise the integrity of the piping and could result in external leakage. Vibrations lead to multiple cracking. Decrease of efficiency of cooling due to sediments on exterior of the pipe is prevented by operating with 5% of pipe plugged, and by maintaining water quality from secondary circuit and cleaning of pipe with water jet to avoid pipe plugging. Event is caused by ageing.

Event description	Risk and CCF related impact	Event relation to ageing
TRIGA secondary circuit - the circulation pumps have leaks and start very difficult because aspirate false air	Pump failure was highlighted by a reduction of flow, and by increasing of cooling agent temperature at the inlet of primary circuit. When one pump has failed, there is a stand-by pump which can be started. Any failure in secondary circuit leads to increasing temperature of coolant agent in primary circuit. All the pumps operating parameters are monitored.	Wear leads to deterioration of surface, to wall thickness or cracking. Under fretting conditions, fatigue cracks may be initiated at very low stresses. Event is caused by ageing.
TRIGA secondary circuit - the heat exchangers have deposits on the pipes and the necessary heat transfer is not performed in an appropriate way; heat exchanger no. 2 has broken pipes	The external leaks lead to modification of operational parameters. MIC could lead to inadequate operation of heat exchangers. Inadequate heat transfer is monitored (temperature sensors on heat exchanger outlet), and could lead to increase of coolant agent temperature. In case when one line of heat exchanger is lost, there is another stand-by line, which could take over the function of heat transfer.	MIC is characterized by the formation of microbial colonies and associated scale and debris on the surface of the metal. Consequences of corrosion erosion processes are thinning of walls until leakage occurs, depending on the deposition of the eroded particles at different locations. Event is caused by ageing.

There is general agreement that the relation between CCF potential and ageing could be quantified in some way. However, it would be necessary to develop specific new methodology for that and the results of quantification would be burdened with relatively high level of uncertainty.

In case of human factor as possible source of CCF, it was commented that human factor failure potential should be addressed better with human reliability and human factor analysis methods than with CCF analysis. However, it was found that there are some connections to ageing as lack of motivation, other aspects of personnel ageing etc. on negative side, and learning process undergone by every maintenance/operation crew during years on positive side.

The relation between component complexness and CCC-ageing coincidence was discussed, but no unique, unambiguous result was reached. The first idea was that “big” components may show up more intensive connection with ageing in CCF symptoms than “small components”, but this idea was negated with most of the participants (the effects of ageing in case of “big” components can be internally attenuated by different preventive maintenance activities that address other components or other failure modes within the boundary of the same “big” component, on the other hand - “small” electronic components are subject of environmental and ageing effects, which may increase CCF potential).

Another hypothesis discussed was that the safety impact of the CCF-ageing linkage is given with the strength of CCF potential, first of all, with the role of ageing classified as supplementary only (as a consequence of the fact that deterioration of safety qualities of the system caused by ageing is much lower than decreasing of safety due to CCF impacts). However, this idea was not supported very intensively during the discussion. On the other hand, the thesis about much bigger impact of ageing link with CCF than “simple” ageing of individual components, was supported conditionally (should be further refined and supplemented with concrete examples).

In Section 2 of this report, some general remarks were given regarding links between CCF potential and ageing, which were made on the base of analysis performed in NRI. Some of these conclusions were put into the questionnaire and further discussed among participants of Task 5. In the following table, the results of the discussion are presented in the form of other conclusions (some of them are partly correlated with points presented in previous paragraphs).

Table 13: Other conclusions taken from the discussion among APSA Task 5 participants

Conclusions made by NRI specialists	Results of discussion of the conclusions with other participants
There is some evidence about correlation between ageing and factors influencing strength of common cause failure potential.	The conclusion was entirely agreed among project participants during the discussion. Additional examples from specific operational experience were given in support of the conclusion.
Common cause failures may be treated also as one specific item of methodologies of covering ageing phenomenon in the studies of probabilistic safety assessment.	Entirely agreed. Supported with specific operational experience of the participants. The participants are collecting CCF related operational experience so that they may use it in future for supporting theoretical assumptions by real data. The problem is that such experience is fairly rare so that gathering operational data from big number of sources would be highly recommendable.
It is possible to quantify contribution of CCF-ageing link to failure potential by means of probabilistic parameters.	Positive, but pointed out repeatedly that under current circumstances, such kind of quantitative analysis is complicated and may be burdened with excessively high level of uncertainty.
Common cause failures with significant effect of human factor can be frequently screened out at the beginning of ageing related analysis.	Mostly agreed, in one case not. The comment was made that there are special problems with ageing related to human element of NPP operation (human resources for exchange of generations, loss of experience gained during decades). However, it seems that these cases of human factor related problems may not have direct link to CCF-ageing topic.
Some selected component failure modes, which are sensitive to CCF potential, are a priori also candidates for ageing related analysis.	Generally agreed. There are definitely some specific failure modes with higher than average CCF potential (plugging of strainers, loss of piping integrity in aggressive environment), which are also evaluated as pretty ageing related.
„Big“ components usually do not show up more intensive connection with ageing in CCF symptoms than “small” components.	An example was given with emphasize on generally high ageing potential in case of tiny components (of information and control systems) - primarily regarding independent failures, but also including CCFs logically.

Safety importance of CCF-ageing connection is given, first of all, with the common cause failure characteristics of the event.	Not supported completely, not supported with example presented in [14]. The risk impact of independent failure rate increasing due to ageing (contributing to CCF probability value, as well), may be comparable with the impact of CCF coupling factors potential increasing represented with alpha factors values
Even hardly analyzable and quantifiable influence of ageing on CCF potential will have much bigger impact on PSA results than ageing relation to reliability of one specific component.	Agreed. Evaluated as “natural” consequence of general character of PSA models and principle of providing redundancy, where common failure of several mutually redundant components represents much higher risk impact than independent failure of one component. Thus, if independent failure rate of one component is increased pretty much due to ageing, the consequences may be still lower than in case of (not that big) increase of CCF potential due to ageing.

Final summary

The theme of common cause failure potential interference with ageing was proven to be viable and important for safety and risk of nuclear power plants operation during next decades. The topic may become standard part of plant APSA scope at least for nuclear power plants reaching and extending originally planned life. It may be difficult to develop comprehensive methodological support for this kind of analysis, but there is increasing volume of operational information worldwide, which can be transferred into data sets providing many useful inputs into the process of making assumptions, modeling, quantifying and providing recommendations oriented to limitation of this risk contributor.

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Abstract

The investigation of ageing phenomenon impact on CCF potential was the main goal of Task 5 of the EC JRC Ageing PSA (APSA) Network.

This report is devoted to investigation of close links between CCF potential and ageing, and provides expert opinions (based on the questionnaire answers) regarding connection between common cause failure potential and ageing phenomenon, as the influence of the individual prevention factors against CCF.

In the questionnaire, two main topics were discussed:

-What is the strength of relation between the individual CCF coupling factors (contributing to total CCF potential) and ageing phenomenon?

-For those CCF coupling factors, which have been evaluated as coincident with ageing phenomenon (at least medium level of coincidence) - what is the effect of CCF prevention measures on the coupling factor versus ageing relation?

A specific color scale was used to specify the strength value of CCF coupling factor and ageing phenomenon relation and to define the strength of potential influence of prevention factor on the strength of link between CCF potential and ageing phenomena. The strength value assigned in the table was commented (reflection in operational experience, assumptions etc.).

The strength between CCF coupling factors and ageing and the influence of the individual prevention factors against CCF was evaluated based on available operational experience and expert judgments.

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